

Discussion of "Turbulence Measurements with Acoustic Doppler Velocimeters" by Carlos M. García, Mariano I. Cantero, Yarko Niño, and Marcelo H. García

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The discussers congratulate the authors for their important contribution. Although acoustic Doppler velocimetry (ADV) has become a popular technique for last two decades, some researchers, including the authors, pointed out rightly that ADV signal outputs include the combined effects of turbulent velocity fluctuations, Doppler noise, signal aliasing, turbulent shear, and other disturbances. Simply, "raw" ADV velocity data are not "true" turbulence and should never be used without adequate postprocessing (Nikora and Goring 1998; Wahl 2003). Herein the discussers aim to complement the understanding of ADV turbulence measurements by arguing the effects of sampling duration and proximity of solid boundaries. They discuss also practical issues associated with turbulence measurements in natural estuarine systems with acoustic Doppler velocimeters (ADV).

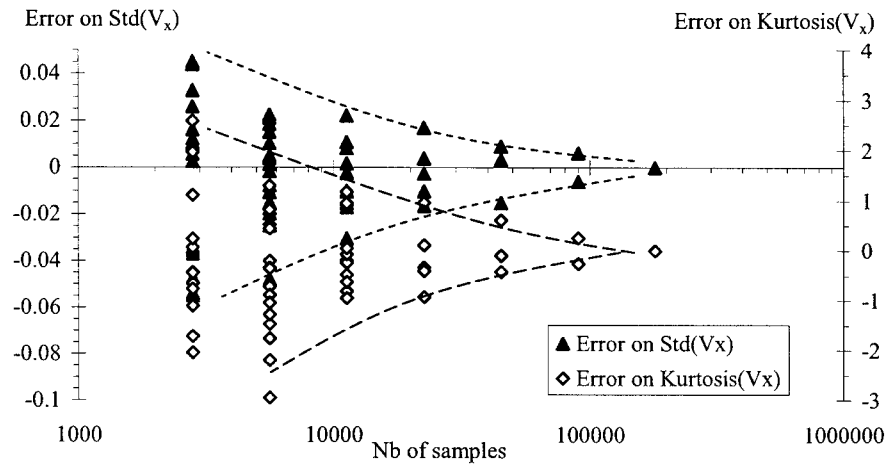
The sampling duration does influence the results since turbulence characteristics may be biased with small sample numbers. Yet, in hydraulic engineering, there has been a great variety of sampling durations used by various researchers in laboratory and field studies without systematic validation. In their study, the authors used a 2-min sampling time corresponding to 6,000 samples maximum, assuming implicitly that such a duration is long enough to describe the turbulence. Basic turbulence studies showed recently the needs for larger sample sizes (e.g., 60,000 to 90,000 samples per sampling location) (Karlsson and Johansson 1986; Krogstad et al. 2005). The discussers performed new experiments in a large laboratory flume (0.5 m wide, 12 m long) with sub- and transcritical flow conditions. The channel was made of smooth PVC bed and glass walls, and the waters were supplied by a constant head tank. Velocity measurements were conducted with a 16 MHz micro ADV equipped with a two-dimensional sidelooking head. Sensitivity analyses were performed in steady flows with 25 and 50 Hz scan rates, total sampling durations T_R between 1 and 60 min, and in both gradually varied and uniform equilibrium flows. The results indicated consistently that the streamwise velocity V_x statistical properties were most sensitive to the number of data points per sample. The first two statistical moments (mean and standard deviations) were adversely affected by sampling durations less than 100 s (less than 5,000 samples). Higher statistical moments (e.g., skewness, kurtosis), Reynolds stresses, and triple correlations were detrimentally influenced for

scan durations less than typically 500 to 1,000 s corresponding to less than 25,000 to 50,000 samples. The findings are consistent with modern experimental studies of turbulence (Karlsson and Johansson 1986). Fig. 1 illustrates the effects of the sample size at a sampling location at 27 mm above the bed on the channel centerline. The data set was "cleaned" by excluding low-correlation and low signal-to-noise ratio samples, and by removing "spikes" using a phase-space thresholding technique (Goring and Nikora 2002; Wahl 2003).

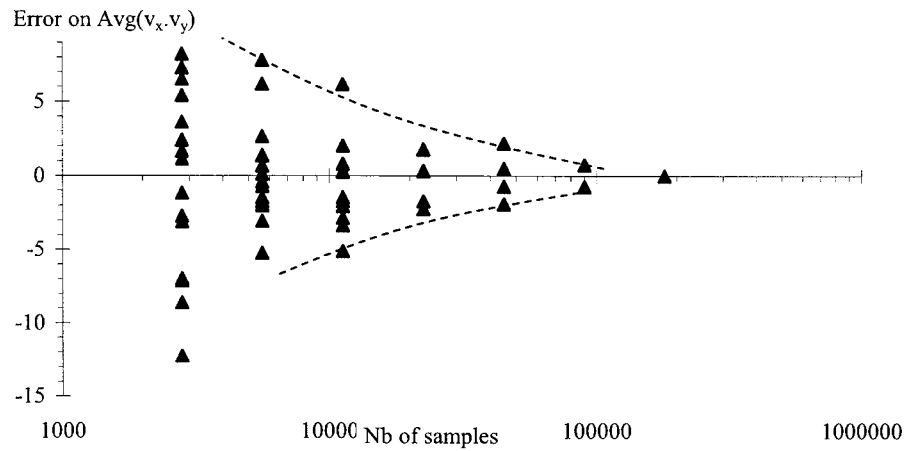
The proximity of a boundary may adversely affect the ADV probe output, especially in small laboratory flumes. Several studies discussed the effects of boundary proximity on sampling volume characteristics and the impact on time-averaged velocity data (Table 1). Table 1 lists pertinent studies, including details of the reference instrumentation used to validate the ADV data (Table 1, column 2) and of the ADV systems (Table 1, columns 3 and 4). These studies highlighted that acoustic Doppler velocimeters underestimated the streamwise velocity component when the solid boundary was less than 30 to 45 mm from the probe sampling volume. Correction correlations were proposed by Liu et al. (2002) and Koch and Chanson (2005) for micro-ADV with 3D downlooking head and 2D sidelooking head respectively. The discussers observed that the effects of wall proximity on ADV velocity signal were characterized by a significant drop in average signal correlations, in average signal-to-noise ratios and in average signal amplitudes next to the wall (Koch and Chanson 2005). Martin et al. (2002) attributed lower signal correlations to high turbulent shear and velocity gradient across the ADV sampling volume. But the discussers observed that the decrease in signal-to-noise ratio with decreasing distance from the sidewall appeared to be the main factor affecting the ADV signal output. Finally, it must be stressed that most past and present comparative studies were restricted to limited comparison of time-average streamwise velocity component. No comparative test was performed to assess the effect of boundary proximity on instantaneous velocities, turbulent velocity fluctuations, Reynolds stresses nor other turbulence characteristics.

The discussers were involved in high-frequency, long-duration turbulence measurements using ADVs in a small estuary (Fig. 2) (Chanson 2003; Chanson et al. 2004). Fig. 3 shows a typical raw signal output for the streamwise velocity component during one such field investigation. The sampling volume was located 0.05 m above the bed for all study duration, and the measured water depth is reported in Fig. 3 (Right vertical axis). While the ADV is well-suited to such shallow-water flow conditions, all field investigations demonstrated recurrent problems with the velocity data, including large numbers of spikes (e.g., Fig. 3, $t=28,000$ – $34,000$ s). Problems were also experienced with the vertical velocity component, possibly because of the effects of the wake of the stem. Practical problems were further experienced. During one field study, the computer lost power and could not be reconnected to the ADV for nearly 50 min (Fig. 3, $t=49,000$ – $52,000$ s). During other field works, the ADV sampling volume was maintained about 0.5 m below the free-surface, implying the need to adjust the vertical probe position up to 3 times per hour. Last, navigation and aquatic life were observed during all field works (Fig. 2). Fig. 2 shows a recreational dinghy passing in

(A) Error on streamwise velocity standard deviation and kurtosis



(B) Error on time-averaged Reynolds stress $\overline{v_x \cdot v_y}$ (where y is the transverse direction)



(C) Error on time-averaged triple correlations $\overline{v_x^2 \cdot v_y}$ (where y is the transverse direction)

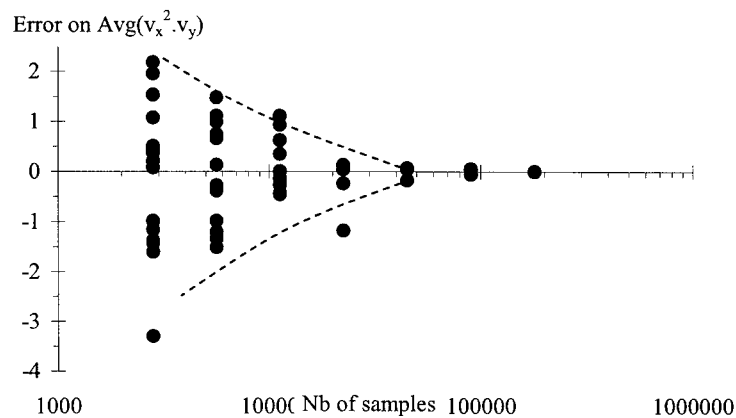


Fig. 1. Effects of data sample size on turbulence characteristics in a 0.5-m-wide, 12-m-long open channel [flow conditions: $Q=0.0404 \text{ m}^3/\text{s}$, $W=0.5 \text{ m}$, $d=0.096 \text{ m}$, $z=27.2 \text{ mm}$, micro ADV (16 MHz) with 2D sidelooking head, sampling rate=50 Hz; velocity range=1 m/s]

Table 1. Experimental Studies of the Effects of Boundary Proximity and Velocity Shear on Acoustic Doppler Velocimetry Data in Open Channels

Reference	Reference probe	ADV device	ADV sampling volume location affected by boundary proximity	Remarks
Voulgaris and Trowbridge (1998)	8 mW Helium-Neon LDV	Sontek ADV 10 MHz 3D downlooking	—	
Finelli et al. (1999)	Hot-film probe Dantec R14 (single-wire)	Sontek ADV Field 10 MHz 3D downlooking	$z < 10$ mm, centerline data	$W=0.13$ m. Acrylic bed and walls.
Martin et al. (2002)	—	Sontek micro ADV 16 Hz 3D downlooking	—	
Liu et al. (2002)	Prandtl-Pitot tube ($\phi=3$ mm)	Sontek micro ADV 16 MHz 3D downlooking	$z < 30$ mm, centerline data	$W=0.46$ m. Aluminum bed, glass walls.
Koch and Chanson (2005)	Prandtl-Pitot tube ($\phi=3.02$ mm)	Sontek micro ADV 16 MHz 2D sidelooking	$y < 45$ mm	$W=0.50$ m. PVC bed, glass walls, $75 \text{ mm} \geq z \geq 7.2 \text{ mm}$ (ADV head touching channel bed).

Notes: y =transverse distance from a sidewall; and z =vertical distance from the invert.



Fig. 2. Field deployment of acoustic Doppler velocimeters [boat passing beside the tripod (foreground left) supporting the ADVs at high tide]

reverse beside the ADVs. The effects of propeller wash and “bow” waves were felt for several minutes as discussed by Chanson et al. (2004). In a few instances, birds were seen diving and fishing next to the ADV location. All these events/disturbances had some impact on the turbulence data.

Careful analyses of ADV signal outputs showed that turbulence properties were inaccurately estimated from unprocessed ADV signals. Even “classical” despiking methods were not directly applicable to unsteady estuary flows. A new three-stage postprocessing method was developed (Chanson et al. 2005). The technique included an initial velocity signal check, the detection and removal of large disturbances (prefiltering), and the detection and removal of small disturbances (despiking). Each stage included velocity error detection and data replacement. The method was applied successfully to long-duration ADV records at high frequency (25 Hz). Both 10 MHz ADV and 16 MHz microADV systems were used. For all investigations, between 10 to 25% of all samples were deemed erroneous. For the data shown in Fig. 3, the number of erroneous samples corresponded to 10% of the records, or 19% of the entire study period including the power

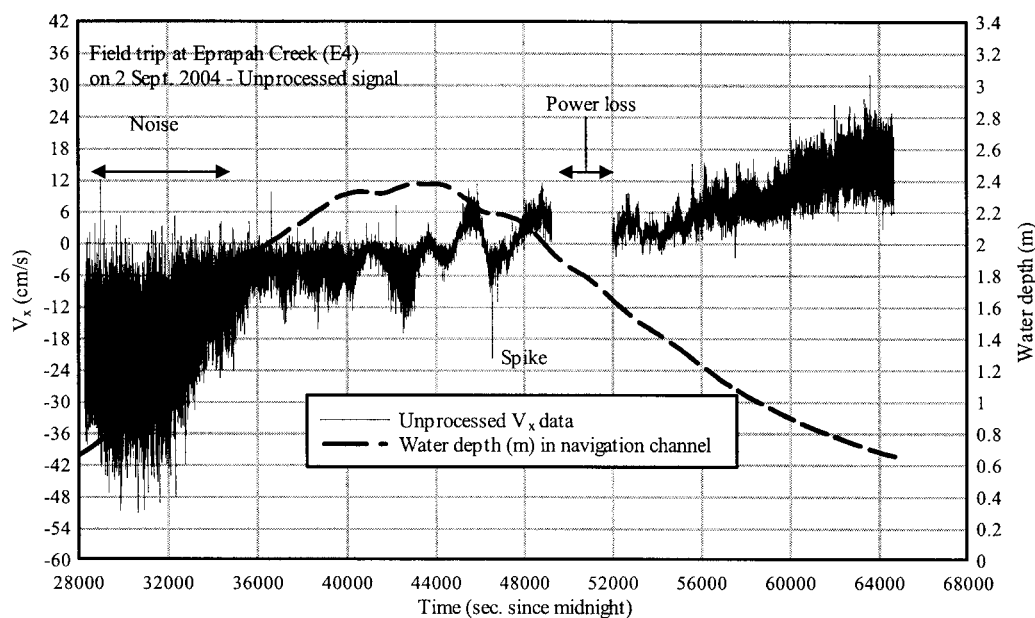


Fig. 3. Field data from ADV deployment in a small estuary: streamwise velocity V_x component (positive downstream, unprocessed “raw” signal) and measured water depth [time in seconds since midnight field work: Sept. 2, 2004, ADV (10 MHz) with 3D downlooking head; sampling rate=25 Hz, continuous sampling; velocity range=0.30 m/s; sampling volume located 0.052 m above bed and 10.8 m from left bank]

failure. Field observations illustrated that unprocessed ADV data should not be used to study turbulent flow properties, including time-averaged velocity components.

In summary, the authors' contribution was a timely notice that acoustic Doppler velocimeters have intrinsic weaknesses and that their signal outputs are not always "true" turbulence measurements. In this discussion, it is demonstrated that in steady open channel flows, the sampling record must be larger than 5,000 samples to yield minimum errors on first and second statistical moments of the velocity components. Significantly longer records (more than 50,000 samples) are required for accurate determination of higher statistical moments (e.g., skewness and kurtosis), Reynolds stresses, and triple correlations. Further ADV signal outputs are adversely affected by the proximity of solid boundaries, particularly when the sampling volume is located less than 30 to 45 mm from the wall. Recent field observations in a small estuary showed also that ADV records may be affected by various disturbances including wildlife and manmade interferences. Comparative analyses of long duration, high-frequency data sets highlighted the needs for advanced postprocessing techniques. It is hoped that the authors' contribution and the present discussion will stress enough the needs to educate and adequately train technicians, engineers, scientists, and researchers deploying ADVs in the field, including portable ADV systems.

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The paper by Garcia et al. deals with the problem of correctly measuring turbulence parameters with acoustic Doppler velocimeters (ADV; trade names ADV for Sontek and NDV for Nortek). The authors focus on the effects of sampling frequency and Doppler noise on turbulence parameters. To avoid loss of turbulence information, they suggest that data should be sampled above a determined frequency. In addition, noise should be removed by estimating the noise contribution. Their approach is based on a model-derived procedure. First, it would have been of interest to compare the modeled spectra with those obtained from their measurements to validate their model and instrument assumptions for the flow cases discussed. Second, the deviation from the $-5/3$ slope in the measured spectra due to filtering and/or noise effects has not been highlighted.

We investigated the authors' conclusions using a Vectrino (Nortek) ADV. Different from their instruments, a Vectrino has four receivers symmetrically spaced around the central emitter. The applied sampling frequencies, the relative position, and the size of the measuring volume, however, were identical to the NDV. Using four receivers allows measuring the vertical velocity component simultaneously in the two planes. This configuration enables the direct estimation of noise effects so that suitable correction procedures such as the one proposed by Hurther and Lemmin (2001; hereinafter called HLP) can be applied. The HLP takes advantage of the redundancy of the vertical velocity obtained in the two instrument planes.

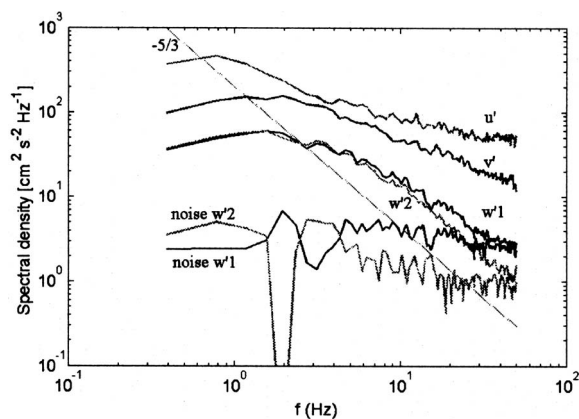


Fig. 1. Turbulence spectra of the u , v , and w velocity components sampled at 100 Hz; also shown are the noise spectra for the two vertical velocities

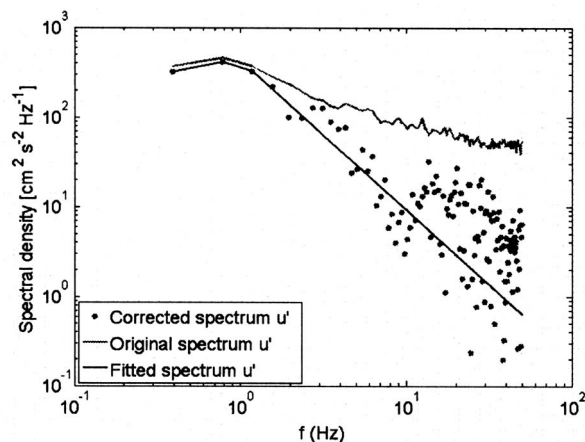


Fig. 2. Original, noise corrected, and fitted spectra for the longitudinal component sampled at 100 Hz

It should be noted that Doppler noise is composed of several contributions that can be estimated (Garbini et al. 1982; Lhermitte and Lemmin 1990, 1994; Hurther and Lemmin 1998; Voulgaris and Trowbridge 1998) or eliminated (Garbini et al. 1982; Hurther and Lemmin 1998, 2001; Blanckaert and Lemmin 2006). For three receiver instruments, such as those used by the authors, the procedure proposed by Voulgaris and Trowbridge (1998) can be applied who emphasize that overestimates have to

be expected. A sufficiently high sampling frequency is required for successful measurements.

Our measurements were carried out in an open channel at the LHE-EPFL. The channel is 0.60 m wide and 17 m long. The bottom was covered with a 0.1-m-thick gravel layer (size range 3–8 mm; $d_{50}=5.5$ mm). In this experiment, water depth and the measuring volume of the instrument were respectively 0.14 m and 0.05 m above the bed. The convective velocity is 0.6 ms^{-1} . Data were recorded about 12 m from the channel entrance where turbulence is well developed for at least 3 min with sampling frequencies of 100, 75, 50, 25, and 10 Hz. The instrument was mounted downward looking with one receiver plane oriented along the flow and the second one in the transversal direction. Two experiments were carried out. In the first one, mean values for correlation and SNR were about 84 and 24 dB. In this experiment we used hydrogen bubbles as “seeding material” (Blanckaert and Lemmin 2006). For all sampling frequencies, the data appeared “clean” with only a few spikes. In the second experiment, mean values for correlation and SNR were 81 and 22 dB without any seeding procedure. Although these quality parameters were high, frequent spikes were observed, in particular in the longitudinal plane.

Following Nezu and Nakagawa (1993), u , v and w denote the velocity fluctuation and u' , v' , and w' denote the RMS values (turbulence intensities). For each of the sampling frequencies, the turbulence intensities and spectra of each velocity were calculated. The noise spectra were obtained using the HLP by calculating the cross spectrum between the two vertical components. The noise spectrum of the longitudinal component u was determined as outlined in HLP and subtracted from the original spectrum of u . To fit a curve to the noise corrected spectrum (NCS), we kept the NCS at the low frequency end and curve fitted the NCS points starting where the $-5/3$ slope is established in the spectrum and ending at the Nyquist frequency. An estimate of the variance can be obtained by integrating the surface under the spectral curve. This was done for all three spectra resulting in u'_{orig} for the original spectrum, u'_{cor} for the NCS, and u'_{fit} for the fitted one.

Fig. 1 shows a typical result for the data sampled at 100 Hz. As can be seen, both of the vertical velocities, (w_1) the longitudinal plane and particularly (w_2) in the transversal plane closely follow the $-5/3$ slope over an extended region. Both noise spectra are nearly flat indicating white noise. Fig. 2 shows spectra of the longitudinal components (original and NCS) as well as a fitted spectrum. Although we can see that the slope of the NCS in the midfrequency range is close to $-5/3$, at the high frequency end, the noise is not completely removed by the HLP method, resulting in significant scatter.

The aforementioned procedure was executed for all velocity components and sampling frequencies. The results for the longitudinal component are summarized in Table 1. It can be seen that

Table 1. Estimates of the Three Turbulence Intensities (in 10^{-2} ms^{-1}) for the Longitudinal Velocity Sampled at Different Frequencies

f (Hz)	$h=0.14 \text{ m (exp 1)}$			$h=0.14 \text{ m (exp 2)}$			$h=0.09 \text{ m}$		
	u'_{orig}	u'_{cor}	u'_{fit}	u'_{orig}	u'_{cor}	u'_{fit}	u'_{orig}	u'_{cor}	u'_{fit}
100	8.83	4.89	4.69	15.16	8.66	6.16	4.69	3.74	3.74
75	7.93	4.89	4.24	13.96	8.06	6.16	5.65	3.74	3.00
50	7.81	4.89	4.69	11.31	6.92	5.47	5.19	3.74	3.00
25	5.47	4.35	4.12	11.83	7.41	4.69	4.89	3.74	3.46
10	4.89	4.24	4.00	7.21	5.65	5.00	5.65	4.12	2.82

u'_{orig} decreases by a factor of almost two between the highest and the lowest sampling frequency. However, it decreases slower between 100 and 50 Hz than between 50 and 10 Hz. The values for the NCS are by a factor of two lower than those of the original spectrum for 100 Hz and remain constant until 50 Hz. They then drop by about 10% for 10 Hz. This difference between the original data and the NCS confirms the observation by Lohrmann et al. (1994) that uncorrected data are biased to higher values. The values obtained from the fitted spectra show a difference of about 10% between the highest and the lowest frequency. In between, the variation is random.

The magnitude of the values from the different spectra indicates the importance of proper noise removal. Comparing u'_{orig} and u'_{cor} , the decreasing tendency in u'_{orig} for decreasing sampling frequency can essentially be attributed to noise effects and not to filtering related to the sampling frequency. If filtering had been the dominant cause of the unresolved velocity scales in the higher spectral range, the slope of the spectra in this region would have been greater than the $-5/3$ value. This is not always the case for different sampling frequencies.

In this study, we documented the importance of proper noise removal. Considering the sampling frequency criteria suggested by Nezu and Nakagawa (1993), turbulence should not be sampled below 75 Hz in our case. However u'_{cor} remains constant down to 50 Hz. In other words, our observation demonstrates that the Vectrino ADV is a robust instrument because it still produces reliable results well below that threshold value. Thus, when proper sampling criteria are respected, filtering due to change in sampling frequency has no effect on the results.

The curve fitting of the noise corrected spectrum was done to determine whether the uncorrected noise and aliasing may affect the estimates. For our results the difference is about 5%. Considering that curve fitting is not an ideal procedure and that other undetermined uncertainties in the measuring procedure remain, this value appears acceptable and indicates that those deviations do not significantly affect the results.

We have applied this procedure to the second data set in which a fairly large number of spikes occurred. For the present analysis, we did not eliminate the spikes from the data set. These spikes may be due to random noise or aliasing. Although aliasing can be dealt with by using procedures modified from those suggested by Franca and Lemmin (2006), random noise is difficult to eliminate from the u , v , and w velocity data. Furthermore, it has to be remembered that due to the system configuration, spikes in one velocity component may also affect the other components. Thus, spike removal procedures such those as suggested by Goring and Nikora (2002) have to be applied with caution. The Vectrino ADV allows for recording beam velocities instead of u , v , and w velocities. This recording has a great advantage in that spikes can be removed individually from each beam time series before constructing the u , v , and w velocities. This allows for a much more objective approach than previous ones (Goring and Nikora 2002).

The results in Table 1 indicate that the overall trends observed in the first data set are reproduced in the second one. However, the level of all values is roughly double that of the first data set. This shows that noise removal by the HLP cannot eliminate the effects of spikes and that spikes have a much more detrimental effect on the quality of the results than the sampling aspect previously mentioned. On the other hand, it appears from our results that sampling at low frequency would be the better strategy in this case. Taking the first data set as reference, the noise corrected and fitted results at low sampling frequencies in the spiked data are

closest to those observed in the first data set at frequencies above the threshold level.

In a final test we applied the HLP to a data set taken in the same channel in a flow of 0.09 m water depth and a convective velocity of 0.32 m s^{-1} , which is about 50% of the convective velocity in the experiments above. Again, we used hydrogen bubble seeding. Results in Table 1 show that the original spectra vary randomly. Thus there is no filtering effect related to the sampling frequency. This is even more obvious in the NCS, which remains constant down to 25 Hz. The fitted data which depend on the indication of a $-5/3$ trend in the spectrum show poor results for the 10 Hz case. Overall these data indicate once more that apart from spike removal, noise removal is the most important process for increasing the reliability of the data.

Our analysis has shown that the recommendations and conclusions by the authors cannot be considered as a universal guide when making turbulence measurements with ADVs. Our investigation has demonstrated that four-receiver ADV instruments, such as the Vectrino, open up new ways to treat data that lead to greatly improved results in turbulent flows. This suggests that using modern ADV instrumentation, turbulence studies can be carried out along the following procedure:

- Ensure that the flow has sufficient scattering targets. Wherever seeding is needed, hydrogen bubble seeding (Blanckaert and Lemmin 2006) has proven to give excellent results in large channel installations where injection of small particles is technically and economically not feasible.
- Record data as beam velocities at sampling frequencies near and preferably above the threshold level as indicated by Nezu and Nakagawa (1993). This allows for subsequent spike removal by de-aliasing procedures (Franca and Lemmin 2006) or data splicing such as spline procedures over adjacent points.
- Transform beam velocities into u , v , and w velocities and apply noise removal procedures such as HLP (Hurthel and Lemmin 2001). The noise removal procedure can be further extended as suggested by Blanckaert and Lemmin (2006).

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The writers appreciate the interest in our paper and the opportunity to clarify the intent and utility of our proposed methodology. Our intention has been to share with the *Journal of Hydraulic Engineering* readership the experience accumulated on ADV measurements over a period of more than 15 years at the University of Illinois at Urbana-Champaign. However, it is important to realize that the proposed methodology can be used to analyze the signal generated by any other sensor used for mean flow and turbulence measurements (e.g., hot-wire anemometer, laser Doppler velocimeter, etc.).

Our hope is that other experimentalists will avoid some of the pitfalls we have encountered along the way and will also be able to take maximum advantage of available flow measurement technology.

In what follows, we will respond to the issues raised by the discussers.

Response to Discussion by Bahareh Doroudian, David Hurther, and Ulrich Lemmin

Comment

First, it would have been of interest to compare the modeled spectra with those obtained from their measurements in order to validate their model.

Response

A comparison between the modeled [Eq. (8) in the paper] and the observed power spectra is included in Fig. 1.

The observed spectrum (characterizing fluctuations in the longitudinal water velocity component series) was computed on the basis of one of the eleven three-dimensional water velocity time series used in the paper to validate the acoustic Doppler velocimeter performance curves (APCs). The analyzed signal was recorded for 2 min using a velocity range of 250 cm/s and a recording frequency of 50 Hz (6,000 samples). The mean and variance values of the longitudinal water velocity signal were 56.04 cm/s and 79.95 cm²/s², respectively. The noise energy level for the analyzed signal, estimated using the "spectral analysis" method proposed by Voulgaris and Trowbridge (1998), was 0.65 cm²/s. The modeled spectrum was computed as the addition of the turbulence spectrum plus the noise spectrum. The turbulence spectrum was estimated using the model from Eq. (8) in the paper and the observed flow turbulence parameters (the scale of the energy containing eddies, L is equal to the depth=0.282 m, and the convective velocity in the longitudinal direction at the measurement point is $U_c=0.58$ m/s). The noise spectrum was estimated using the observed noise energy level assuming that the noise presents white noise characteristics. Good agreement is observed in Fig. 1 between the observed and modeled spectra validating the adopted model.

Comment

Second, the deviation from the $-5/3$ slope in the measured spectra due to filtering and/or noise effects has not been highlighted.

Response

ADV filtering effects in the measured spectra were carefully discussed in the first portion of the paper. Fig. 2 (in the paper) showed the gain factor of the nonrecursive digital filter implemented in ADV for given internal and external sampling frequencies. Besides, Fig. 4 (in the paper) shows the effects of the analog filter (response time of the instrument) with cut-off frequency f_s (internal ADV sampling frequency), and the level of aliased energy with frequencies in the range $f_s/2 \leq f < f_s$ in the original (unsampled) time series. Such energy is folded back through the sampling process and confused with resolved energy corresponding to frequencies in the range $0 \leq f < f_s/2$. For the internal sampling frequencies commonly used for ADV instruments (see Table 1 in the paper), the amount of aliased energy is negligible.

Regarding noise effects, Fig. 2 shows the deviation from the $-5/3$ slope in the power spectrum due to noise effects for the flow conditions analyzed in Fig. 1. Power spectra were computed using the adopted model for the flow conditions analyzed in Fig. 1 with different noise energy levels ($E_{I,n,observed}=0.65$ cm²/s). The higher the noise energy level present in the signal the more difficult it is to observe a $-5/3$ slope in the measured spectra.

Comment

The discussers investigated the writers' conclusions through measurements carried out using a Vectrino (Nortek) ADV in an open channel flow at the Environmental Hydraulics Laboratory of the Ecole Polytechnique Fédérale de Lausanne (LHE-EPFL). The discussers concluded that decreasing tendency in u'_{orig} (standard deviation of the recorded energy) for decreasing sampling frequency can essentially be attributed to noise effects and not to filtering related to the sampling frequency.

Response

The discussers reported the standard deviation of different velocity signals (sampled with different recording frequencies) com-

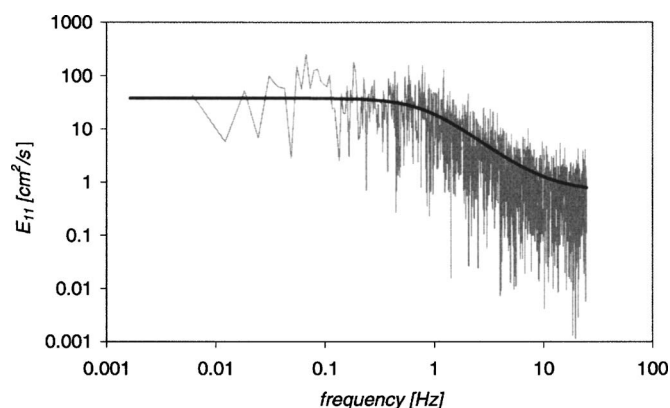


Fig. 1. Comparison between modeled (thick line) and observed spectra (thin line) for the water velocity signal recorded using a recording frequency of 50 Hz (6,000 samples). The analyzed signal is one of the eleven 3D water velocity time series used in the paper to validate the APCs.

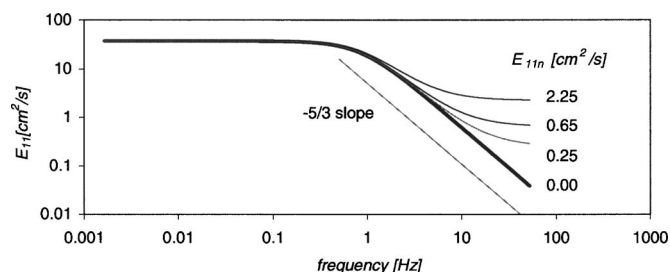


Fig. 2. Deviation from the $-5/3$ slope in the power spectra due to noise effects for the flow conditions analyzed in Fig. 1. Different noise energy levels are analyzed (E_{11n} observed = $0.65 \text{ cm}^2/\text{s}$).

puted integrating the original spectrum (u'_{orig}) and the noise corrected spectrum (u'_{cor}). The discussers highlighted the difference (also mentioned in our paper) between the original data and the NCS confirming the observation by Lohrmann et al. (1994) that uncorrected data are biased to higher values. The reported results are analyzed here as well as the discussers' conclusion that the tendency of the standard deviation of the recorded energy to decrease as the sampling frequency decreases can essentially be attributed to noise effects and not to digital filtering related to the sampling frequency. Here, the analysis will focus on the data reported by the discussers for experiment 1, which presents the best quality of the velocity signals, since seeding material was

used (hydrogen bubbles) and the data appeared "clean" for all sampling frequencies, with only a few spikes, as it was reported by the discussers.

Table 1 presents an extended analysis of the data reported by the discussers. First, the dimensionless frequency $F = f_R L / U_c$ for the tested flow conditions (water depth was 0.14 m and the convective velocity was 0.6 m/s) and the selected instrument configuration (different recording frequencies of 100, 75, 50, 25, and 10 Hz), are introduced. Table 1 also includes the noise energy, $u_n'^2$, which is computed as the difference between the original signal energy, $u_{orig}'^2$, and the corrected signal energy, $u_{cor}'^2$; and the ratio $u_n'^2 / u_{cor}'^2$ for each velocity signal. The noise energy level (E_{11n}) computation is based on the fact that the noise detected in the signal presents white noise properties (flat spectrum), which has also been observed by the discussers [i.e., for $f_R = 100 \text{ Hz}$, $E_{11n} = 54.1 \times 10^{-4} \text{ m}^2/\text{s}^2 / (100 \text{ Hz}/2)$]. Finally, the last two columns include the values of filtered energy and filtered noise energy, respectively. The values of filtered energy are computed as the difference between the energy of the original signal sampled at $f_R = 100 \text{ Hz}$ and the energy of the original signals sampled using different recording frequencies smaller than 100 Hz [e.g., for $f_R = 25 \text{ Hz}$ the filtered energy is computed as the $= u_{orig}'^2(f_R = 100 \text{ Hz}) - u_{orig}'^2(f_R = 25 \text{ Hz})$]. The value of filtered noise energy is computed assuming a constant energy level E_{11n} , which is characteristic of white noise (flat spectrum). The filtered noise energy level is computed as $E_{11n}(100 \text{ Hz} - f_R)/2$. The constant noise energy level $E_{11n} = 10^{-4} \text{ m}^2/\text{s}$ is adopted for all the recording frequencies based on the noise reported for the case of $f_R = 100 \text{ Hz}$.

The values reported in Table 1 make it possible to draw the following conclusions:

1. The discussers cited the sampling frequency criteria suggested by Nezu and Nakagawa (1993) with regard to the fact that turbulence should not be sampled below 75 Hz in the case reported by the discussers. The same conclusion can be stated based on the value of F reported in Table 1 and the necessary condition mentioned in the paper of a value of $F > 20$ to obtain a good representation of flow turbulence using ADVs.
2. Very high noise energy is detected in the signal as it is shown through the ratio between the noise energy and the corrected signal energy.
3. The noise energy level obtained is about $E_{11n} = 10^{-4} \text{ m}^2/\text{s}$ and can be assumed to be fairly constant for all the used recording frequencies.
4. The values of filtered energy and filtered noise energy show a good agreement, which implies that most of the energy filtered in the signal corresponds to noise energy because of the high noise energy level present in the original signal. For

Table 1. Extended Analysis of Data Presented in the Discussion for Experiment 1

f_R (Hz)	F	$u_{orig}'^2$ (cm^2/s^2)	$u_{cor}'^2$ (cm^2/s^2)	$u_n'^2$ (cm^2/s^2)	$u_n'^2 / u_{cor}'^2$ (%)	E_{11n} (cm^2/s)	Filtered energy (cm^2/s^2)	Filtered noise energy (cm^2/s^2)
100	23.33	78.0	23.9	54.1	226	1.08		
75	17.50	62.9	23.9	39.0	163	1.04	15.1	14.2
50	11.67	61.0	23.9	37.1	155	1.48	17.0	28.4
25	5.83	29.9	18.9	11.0	58	0.88	48.0	42.5
10	2.33	23.9	18.0	5.9	33	1.19	54.1	51.0

the case analyzed, the cut-off frequency of the digital filter is included in the range of frequencies where the total energy is dominated by the noise. The digital averaging (filtering) effects on the turbulence component of the spectra ($u_{corr}^{\prime 2}$) is expected to manifest itself more strongly for signals with lower noise energy levels, such as the signals analyzed in the paper (they did not present any spikes). One of the cited signals, the velocity signal reported in Fig. 1 of this closure, presented a ratio between the turbulent energy ($u_{corr}^{\prime 2}$) and the total energy ($u_{orig}^{\prime 2}$) = 79.6%. The ratio between the noise energy and the turbulent energy (25.7%) is smaller than all the values of this ratio presented in the Table 1 for the experiment 1 data set presented for the discussor.

5. The analysis of the data reported in the discussion shows that they correspond to particular conditions, where the noise energy dominates the total energy in the recorded signal, which is not convenient for ADV measurements. These noise-dominated conditions can be expected for low energy turbulent flows or in sampling conditions with high noise energy level (see Figs. 14, 15, and 16 of the paper). The effect of the digital averaging due to the ADV sampling strategy cannot be distinguished for the cited conditions because the high frequency portion of the spectra is dominated by noise. It is recommended that an effort is made for improving the signal quality during the measurement process to reduce the noise energy level, thus avoiding any spikes in the signal and reducing noise energy levels. This improvement can be done through a sensitivity analysis of sampling configurations parameters (sampling frequency, velocity range, size of the measurement volume, etc.) defining the optimum sampling configuration for each region of the flow where the flow turbulence characterization is intended (close to the bottom boundary, close to the free surface, etc.). The noise removal procedure in the postprocessing of the water velocity signal may not be enough to ensure a good characterization of the flow turbulence.
6. The writers would also like to point out that hydrogen bubbles as used by the discussors may not provide the best choice for seeding material because of their high buoyancy, particularly in low turbulence environments where turbulence-induced dispersion can be expected to be rather low.

Finally, the writers would like to stress that the analysis presented in the paper is based on the digital treatment of the signal after it has been sampled and does not make any assumption on the way the signal has been sampled, which makes the analysis applicable to a wide range of instruments and measuring conditions.

In closing, the writers would like to thank the discussors for providing an independent data set to extend and to test further the analysis presented in the paper.

Response to discussion by H. Chanson, M. Trevethan, and C. Koch

Comment

The discussors congratulate the authors for their important contribution. The discussors mentioned that, simply, "raw" ADV velocity data are not "true" turbulence and should never be used without adequate postprocessing.

Response

The writers thank the discussors for their kind comments about the paper and also support the fundamental need, as expressed throughout the paper and in this closure, for carefully conducted data recording and post-processing.

Comment

The discussors aim to complement the understanding of ADV turbulence measurements by arguing the effects of sampling duration and proximity of solid boundaries. They discuss also practical issues associated with turbulence measurements in natural estuarine systems with acoustic Doppler velocimeters (ADV).

Response

The writers recognize the importance of sampling duration on the results of flow turbulence characterization, since turbulence characteristics may be biased with a small number of samples is used. However, the authors would like to stress that the optimum sampling time for given turbulence parameters is case dependent and no universal rule should be used in this regard (e.g., minimum number of samples, etc.).

Recently, the writers have published an article regarding confidence intervals in the determination of turbulence parameters (Garcia et al. 2006). Confidence intervals were defined using the moving block bootstrap technique (MBB). It is strongly recommended that such methodology be used to define the optimum sampling time for flow turbulence characterization to obtain a defined uncertainty level in the computed turbulence parameters for each region of the flow where the turbulence characterization is intended (e.g., close to the boundary, close to the free surface, etc.).

The writers' experience also agrees with the discussors' comments in relation with the sampling duration required to obtain accurate values of statistical moments such as skewness, kurtosis, or Reynolds stresses and triple correlations, which is an order of magnitude larger than that required for mean and second order moment.

The writers also agree with the fact that the proximity of a boundary may affect adversely the ADV probe output, especially in small laboratory flumes. The writers would like to add to the detailed literature review presented by the discussors, the article recently published by Precht et al. (2006).

The writers also agree with the discussors when stressing that most past and present comparative studies have mainly been restricted to limited comparison of time-averaged streamwise velocity components. No comparative test seems to have been performed to assess the effect of boundary proximity on instantaneous velocities, turbulent velocity fluctuations, Reynolds stresses, or other turbulence characteristics.

Comment

It is hoped that the authors' contribution and the present discussion will stress enough the needs to educate and adequately train technicians, engineers, scientists, and researchers deploying ADVs in the field, including portable ADV systems.

Response

Based on the discussors' comments on the needs to educate and adequately train technicians, engineers, scientists, and researchers deploying ADVs in the field, the writers developed the following

general guidelines (on the basis of the writers' and discussers' contributions) to perform flow velocity measurements representative of flow turbulence using ADVs.

Task Description

1. Definition of the objectives of the study (characterization of mean values, turbulent kinetic energy, Reynolds stresses, turbulence length, and time scales, etc.).
2. Definition of the flow regions where the flow turbulence characterization is intended (e.g., near bottom surface, near free surface, around objects, etc.).
3. Determination of sampling duration for each flow zone depending on the objective of the study as defined in step 1.
4. Determination of the optimal sampling frequency in each region of the flow required to characterize flow turbulence parameters (i.e., dimensionless frequency $F=f_R L/U_c > 20$, where f_R =ADV recording frequency, L =energy containing eddy length-scale, and U_c =convective flow velocity).
5. Definition of the optimum ADV sampling configuration (i.e., velocity ranges, size of the measuring volume, etc.) for each region of the flow and the selected sampling frequency. The optimum ADV configuration provides the best signal quality for the observed flow conditions. It is recommended that a sensitivity analysis is performed for each region of the flow to maximize the quality of the signal parameters. Also recommended is the addition of adequate seeding particles in suspension to the flow to improve the signal quality. No spikes should be present in the signal.
6. Recording water velocity signals, checking the time evolution of the signal quality parameters and the physical parameters of the fluid.
7. Processing of the signal to remove spikes and replacing them in cases where the object of the study requires analyzing the temporary correlation of the signal.
8. Processing of water velocity signals to define the noise energy level in the recorded signal.
9. Computation of the turbulence parameters required in the study and/or project, correcting the effects of the Doppler noise on the basis of the detected Doppler noise energy levels (Garcia and Garcia 2006).
10. Definition of confidence intervals of each of the computed turbulence parameters (Garcia et al. 2006).

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Discussion of "Vertical Dispersion of Fine and Coarse Sediments in Turbulent Open-Channel Flows" by Xudong Fu, Guangqian Wang, and Xuejun Shao

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The authors have proposed a useful prediction model for vertical concentration distribution that considers the effects of lift force and the sediment stress gradient, in addition to turbulent diffusion and gravitational settling of particles characterized in the traditional advection-diffusion equation. The discussor would like to mention the following points regarding the paper:

1. It is shown that the parameter γ (i.e., the inverse of the turbulent Schmidt number) increases with particle volumetric concentration C and particle diameter d_p . The authors found that the parameter γ is greater than unity and increases toward the bed, being close to unity for fine sediments and considerably larger for coarse ones. The discussor has already obtained such a variation for γ in one of his previous studies (Kaushal and Tomita 2002) in multisized particulate slurry flow through a pipeline. They obtained the following expression for the parameter β (which is equivalent to the parameter γ used by the authors) for the j th particle size across the pipe cross section:

$$\beta_j = 1.0 + 0.125(d_j/d_{wmdf})e^{4.22C_{vj}/C_{vss}} \quad (1)$$

where d_j = j th particle size; $d_{wmdf}=(\sum_{j=1}^n C_{vj}d_j)/(\sum_{j=1}^n C_{vj})$, the weighted mean diameter in the efflux sample; C_{vj} and C_{vss} =composite and j th size particle volumetric concentration, respectively, in the efflux sample; and C_{vss} =static settled concentration. In Eq. (1), C_{vj}/C_{vss} and d_j/d_{wmdf} are used as the correlating parameters, since C_{vss} represents the highest achievable concentration by gravity settling and d_{wmdf} =representative particle size. Because C_{vss} and d_{wmdf} are constants for the particle size distribution in Eq. (1), β increases with particle volumetric concentration and particle diameter. Further, β will always be greater than unity and increases as particle concentration increases toward the bed, being close to unity for fine sediments and considerably larger for coarse ones.

2. The authors observed that the concentration does not monotonously increase toward the bed as the effects of lift force and sediment stress gradient become significant in medium and coarse sediments and need to be considered below the 0.1 flow depth. The discussor has observed similar trends in pipeline flow of slurry in one of his recent studies (Kaushal et al. 2005). Measured concentration profiles show a distinct change in shape for the coarser particle size (480 μ m), with higher concentrations at lower velocities. It was observed that the maximum concentration at the bottom does not change and extends up to the center of the pipeline, thus making a sudden drop in the concentration in the upper half of the pipeline. The reason for such a distinct change in the shape of the concentration profiles was attributed to the slid-

Table 1. Experimental Data Used by Discussor [Kaushal and Tomita (2003)] (Reprinted with Permission from Executive Director, JSCE)

S. No.	Author	Geometry	Material	Particle size distribution			Range of mean velocity (m/s)	Range of concentration C_{vf} (%)
				Size fractions range (μm)	Mean diameter (μm)	% of each size fraction (%)		
1.	Vanoni (1942)	Open channel (width=845 mm, depth of flow=72 mm to 140 mm)	Sand mixed with water ($d_{50}=100 \mu\text{m}$)	20–60	40	25	1.0 to 1.5	0.0075 to 0.052
				60–100	80	25		
				100–140	120	25		
				140–180	160	25		
			(d ₅₀ =133 μm)	43–83	63	25		
				83–163	123	25		
				163–203	183	25		
				203–283	243	25		
2.	Morales (1976)	Open channel (width=200 mm, depth of flow=53 mm to 123 mm)	Sand mixed with water ($d_{50}=120 \mu\text{m}$)	0–30	15	35	1.25 to 2.11	6.0 to 3.12
				30–70	50	25		
				70–100	85	20		
				100–500	300	20		
3.	Winterwerp et al. (1990)	Open channel (width=300 mm, depth of flow=53 mm to 99 mm)	Sand mixed with water ($d_{50}=120 \mu\text{m}$)	0–80	40	12.5	1.0 to 2.05	3.0 to 30.0
				80–120	100	12.5		
				120–200	160	37.5		
				200–240	220	37.5		
4.	Samaga et al. (1985)	Open channel (width=400 mm, depth of flow=35 mm to 65 mm)	Sand mixed with water ($d_{50}=155 \mu\text{m}$)	105–120	112.5	25	1.0 to 2.5	0.05 to 0.8
				120–155	137.5	25		
				155–170	162.5	25		
				170–205	187.5	25		

ing bed regime for coarser particles at lower velocities and higher concentrations.

- The authors observed large errors in concentration distribution by the traditional advection–diffusion equation when it is applied to flows with coarse sediments or high concentrations. The discussor has already drawn the same conclusion for fine and coarse sediments with a wide range of particle concentrations and flow velocities in turbulent open-channel flows in one of his previous studies (Kaushal and Tomita 2003). The discussor compared the concentration distributions predicted by the traditional advection–diffusion model and measured by Samaga et al. (1985), Vanoni (1946), Morales (1976) and Winterwerp et al. (1990). In total, 48 concentration profiles were considered. Table 1 gives the ranges covered for different parameters. For almost all the data, except for some at lower concentrations, the concentration profiles were more asymmetric than those obtained experimentally. For almost all 48 data points, the deviations were systematic, and there was a maximum overprediction of approximately 45% at the bottom ($y/H=0.1$) of the open channel and an underprediction of approximately 35% at the top ($y/H=0.9$) of the open channel, where y is the height from the channel bottom and H is the depth of flow. The discussor then modified the traditional advection–diffusion model by considering β_j as given by Eq. (1) instead of unity in the traditional advection–diffusion model. The eddy viscosity of a liquid in an open channel was determined by using van Rijn (1987) model, and the settling velocity of particles was determined by using the equations of Richardson and Zaki (1954). For almost all the data, the modified model gives an

exact fit between measured and predicted overall concentration profiles. Furthermore, the model was able to predict satisfactorily the unexpected concentration profiles for coarser particles at lower flow velocities where concentration does not monotonously increase toward the bed. According to the Richardson and Zaki (1954) equation for hindered settling velocity and Eq. (1) proposed by Kaushal and Tomita (2002) for particle diffusivity used in the modified model, the settling velocity reduces and particle diffusivity increases drastically at higher concentrations. Also, when the coarser particles are transported at lower flow velocities in the open channel, the concentration in the bottom portion of the pipeline has a large value because of gravitational effects. The large concentration results in a drastic reduction in particle settling velocity and a tremendous increase in particle diffusivity, thus making the concentration gradient almost negligible in the bottom portion of the pipeline, as suggested by the advection–diffusion equation.

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Closure to "Vertical Dispersion of Fine and Coarse Sediments in Turbulent Open-Channel Flows" by Xudong Fu, Guangqian Wang, and Xuejun Shao

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The writers thank D. R. Kaushal for his interest in our paper and for his useful comments on sediment diffusivity in turbulent open-channel flows. The writers are pleased to see similar conclusions that the discussor has drawn through a different approach.

1. The discussor has proposed an empirical equation for the parameter γ (i.e., the inverse of the turbulent Schmidt number). His equation also suggests that γ increases with sediment concentration and sediment diameter and is close to unity for fine sediments and considerably larger for coarse sediments. Notice that his equation was established for multisized particulate slurry flows through pipeline. Under single-sized sediment-laden flows considered in our paper, his equation becomes

$$\gamma = 1.0 + 0.125e^{4.22C_{vf}/C_{vss}} \quad (1)$$

where C_{vf} = local sediment volumetric concentration and C_{vss} = maximum sediment volumetric concentration attributable to gravitational settling. From this equation, the value of γ is greater than unity and increases with the local sediment concentration, being independent of sediment diameter. Moreover, since C_{vf}/C_{vss} is nonnegative and less than unity, γ will range from 1.12 to 9.50. In contrast, Fig. 8 in our

paper suggests that the value of γ could be lower than 1.1 and much higher than 10.0 near the bed, depending on sediment diameter and local concentration.

The writers compared the γ values calculated by the kinetic model in our paper with those predicted by Eq. (1) under the experimental conditions of Einstein and Chien (1955) and Wang and Qian (1989). In the calculation, C_{vss} in Eq. (1) takes a value of 0.64 for single-sized sediments. The results are presented in Fig. 1, where $\eta = y/H$; y = height from the bed; and H = flow depth. Since the local concentration is relatively small for the four runs ($C_{vf} < 0.13$), the predicted value of γ by Kaushal's model is less than 1.3 and greater than 1.12, not being close to unity for fine sediments (0.15 mm for SQ2 and 0.274 mm for S12). In contrast, the kinetic model predicts a value close to unity as $\eta > 0.2$ for SQ2 and S12. Meanwhile, the predicted value of γ by the kinetic model is much higher than that by Kaushal's model, since $\eta < 0.1$ for S2 and S7, where sediment diameter is 1.3 mm and 0.94 mm, respectively. The reason for this difference may be ascribed to the effects of lift force and the sediment stress gradient, which affect sediment vertical diffusion and have been accounted for in the kinetic model.

2. Nonmonotonous concentration distribution in the vertical direction has been observed in both open channel flows (Bouvard and Petkovic 1985) and duct flows (Wang and Ni 1990). In contrast to Kaushal's observation, Bouvard and Petkovic (1985) and Wang and Ni (1990) showed that sediment concentration could have its maximum value above the bed in dilute flows. In our recent work (Wang et al. 2006), the kinetic model developed in our paper was adopted to characterize the nonmonotonous concentration distribution, and Bouvard and Petkovic's (1985) observations were successfully reproduced. The effect of the sediment stress gradient is found to be more important than that of lift force in determining nonmonotonous distribution under Bouvard and Petkovic's (1985) conditions. For flows carrying coarse sediments with high concentrations, interactions (e.g., collisions and frictions) among sediment particles and between sediment and solid bed frequently occur. This may result in significant sediment stress and, correspondingly, great diffusivity of coarse sediments. This may help explain Kaushal's observation that the maximum concentration at bottom does

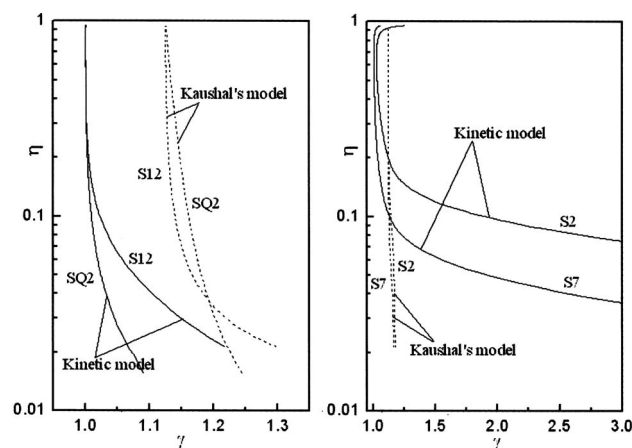


Fig. 1. Comparison of the γ values calculated by the kinetic model with those predicted by Kaushal's model

not change and extends up to the center of the pipeline in slurry flows carrying coarse sediments (480 μm) with higher concentrations at lower velocities.

3. The traditional advection-diffusion (AD) equation may produce large errors in predicting the sediment concentration profile when it is applied to flows with coarse sediments and/or high concentrations. Extensive studies have been devoted to improving this equation, and one way is to establish a useful model for γ instead of unity. The discussor has proposed such a model, which accounts for the effect of sediment concentration on sediment diffusivity and may be applicable for predicting a distribution in which the concentration gradient is almost negligible in the bottom portion of pipeline. However, as suggested by the writers, since both sediment diffusivity and settling velocity are positive parameters, the traditional AD equation cannot predict a distribution where $\partial C_{vf}/\partial y > 0$, although it may reproduce a distribution with a negligible concentration gradient. This drawback cannot be overcome through modifying only the sediment diffusivity formulation, e.g., finding a more appropriate model for γ . As mentioned in our paper, the traditional AD equation accounts for two effects, i.e., settling attributable to gravity and turbulent diffusion attributable to sediment-turbulence interaction, without taking into

account the effects of lift force and the sediment stress gradient. In flows or flow regions where turbulent diffusion gets less dominant and the sediment stress gradient becomes important, the traditional AD equation will produce large errors and needs to be corrected. In this sense, a corrected AD equation along with an appropriate γ model is desirable.

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